The Neutrino Future

and

The Proton driver

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Proton Driver Workshop
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The Neutrino Scene

We do not know how many neutrino mass eigenstates there are.

If the Liquid Scintillator Neutrino Detector (LSND) experiment is confirmed, there are more than 3.

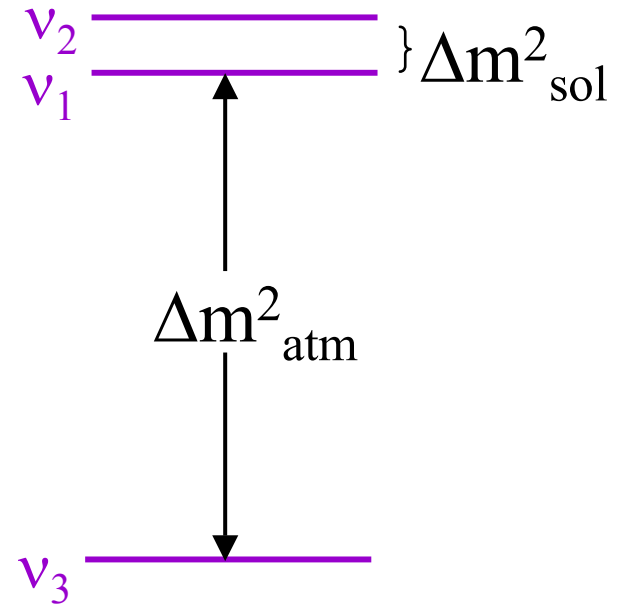If LSND is not confirmed, nature may contain only 3 neutrinos.

Then, from the existing data, the neutrino spectrum looks like —

Normal

ν_3

(Mass)$_2$

Δm^2_{atm}

ν_2
ν_1 } Δm^2_{sol}

or

Inverted
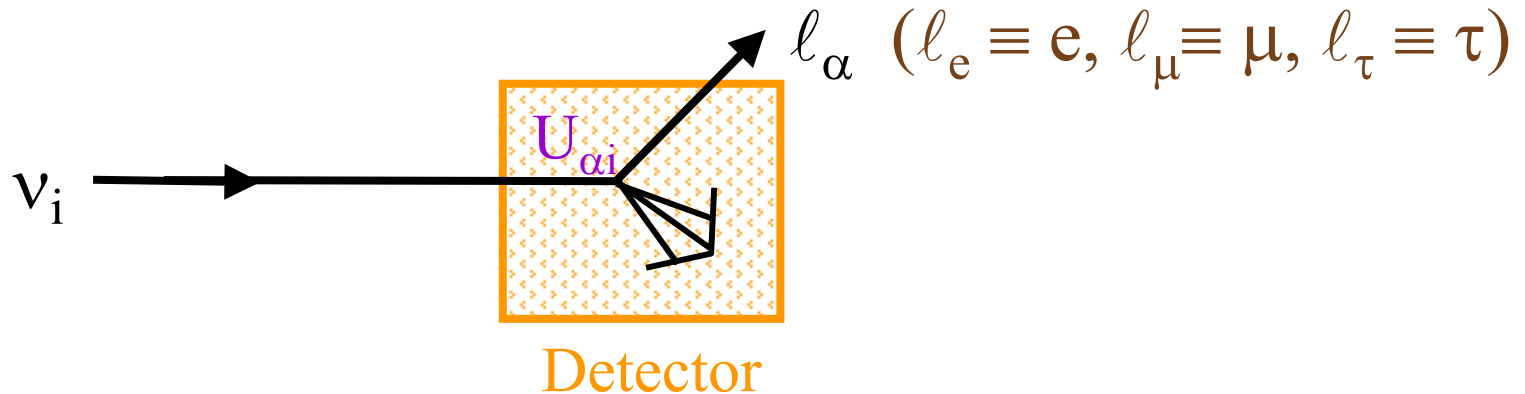
ν_2
ν_1 } Δm^2_{sol}

Δm^2_{atm}

ν_3
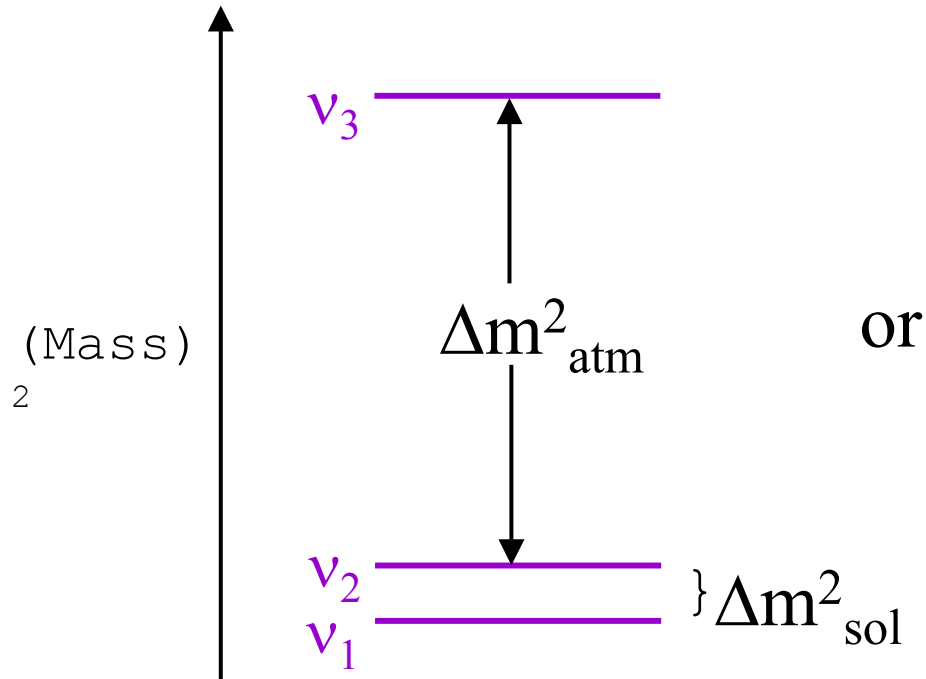
$$\Delta m^2_{sol} \cong 8 \times 10^{-5} \text{ eV}^2, \quad \Delta m^2_{atm} \cong 2.5 \times 10^{-3} \text{ eV}^2$$

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Generically, SO(10) grand unified models favor ▬.

▬ is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

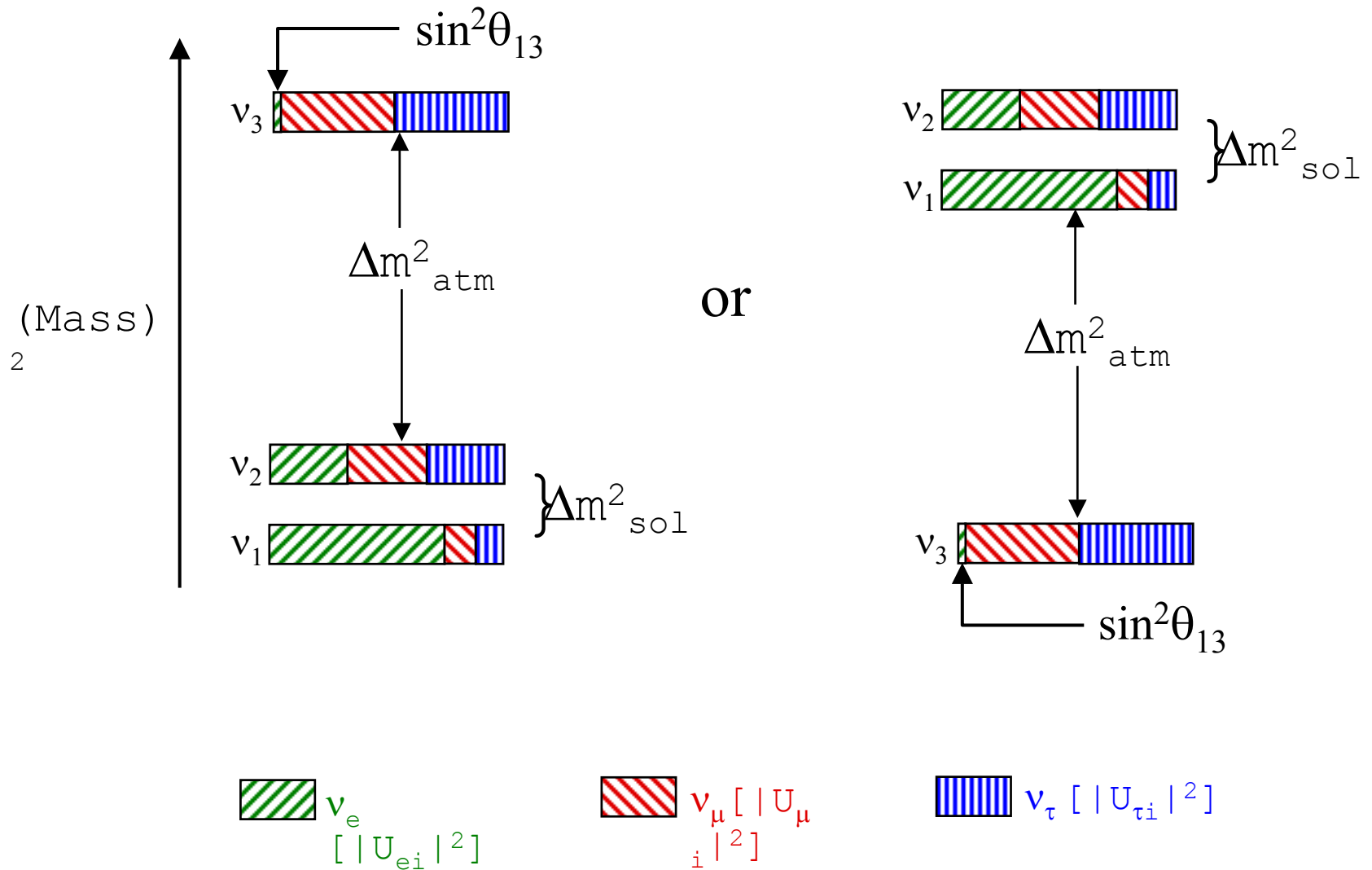The symmetry might be something like $L_e - L_\mu - L_\tau$ conservation.

The Unitary Leptonic Mixing Matrix U

$\ell_\alpha \quad (\ell_e \equiv e, \, \ell_\mu \equiv \mu, \, \ell_\tau \equiv \tau)$

$U_{\alpha i}$

ν_i

Detector

The component of ν_i that creates ℓ_α is called ν_α, the neutrino of flavor α.

The ν_α fraction of ν_i is $|U_{\alpha i}|^2$.

The spectrum, showing its approximate flavor content, is —

$\sin^2\theta_{13}$

ν_3

Δm^2_{atm}

(Mass)$_2$

ν_2

ν_1

$\}\Delta m^2_{sol}$

or

ν_2

ν_1

$\}\Delta m^2_{sol}$

Δm^2_{atm}

ν_3

$\sin^2\theta_{13}$

ν_e $[|U_{ei}|^2]$

$\nu_\mu [|U_{\mu i}|^2]$

$\nu_\tau [|U_{\tau i}|^2]$

The Mixing Matrix

Atmospheric   Cross-Mixing   Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

Majorana ~~CP~~ phases

$\theta_{12} \approx \theta_{sol} \approx 32°, \quad \theta_{23} \approx \theta_{atm} \approx 35\text{-}55°, \quad \theta_{13} \lesssim 15°$
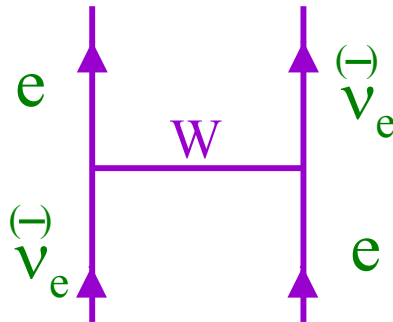
δ would lead to $P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. ~~CP~~

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.
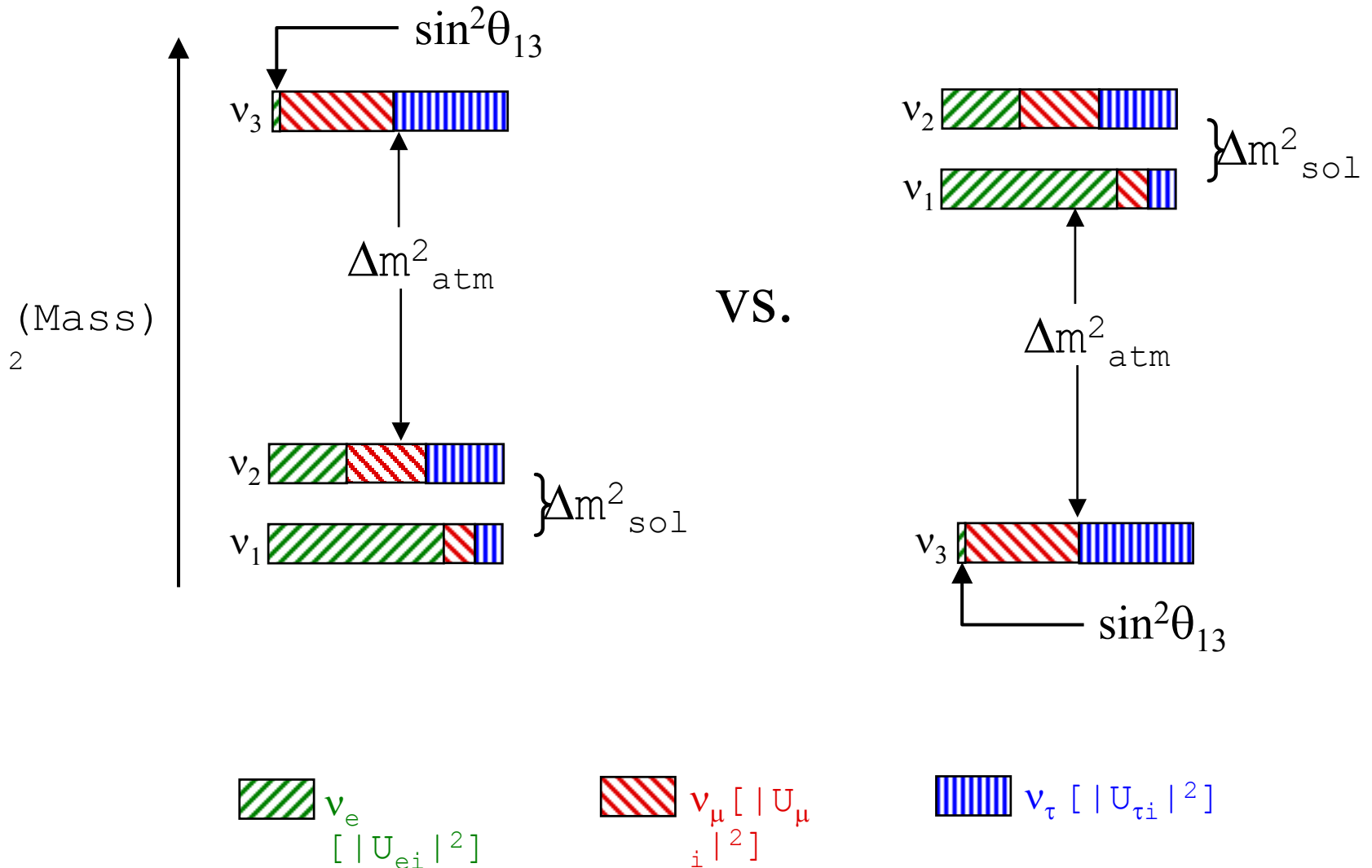
How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,

$$e \quad \overset{(-)}{\nu}_e$$

W

$$\overset{(-)}{\nu}_e \quad e$$

raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

$\sin^2\theta_{13}$

ν_3

ν_2

(Mass)$_2$

Δm^2_{atm}

ν_2

ν_1

$\}\Delta m^2_{sol}$

vs.

ν_1

$\}\Delta m^2_{sol}$

Δm^2_{atm}

ν_3

$\sin^2\theta_{13}$

ν_e $[|U_{ei}|^2]$

$\nu_\mu [|U_{\mu i}|^2]$

$\nu_\tau [|U_{\tau i}|^2]$

The ν_e part of ν_3 must be involved in the experiment.

Note the crucial role of θ_{13}.

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When Δm^2 shrinks, $\sin^2 2\theta$ grows.

At superbeam energies,

$$\sin^2 2\overset{(\overline{\quad})}{\theta_M} \cong \sin^2 2\theta_{13} \left[1 \overset{+}{_{(-)}} S \frac{E}{6 \text{ GeV}} \right].$$

$$\text{Sign}[m^2(\text{—}) - m^2(\text{=})]$$

At oscillation maximum,

$$\frac{P(\nu_\mu \to \nu_e)}{P(\overline{\nu}_\mu \to \overline{\nu}_e)} \begin{cases} >1 \; ; & \equiv \\ <1 \; ; & \equiv \end{cases}$$

The effect is $\begin{cases} 30\% \; ; & E = 2 \quad \text{GeV (NO}\nu\text{A)} \\ 10\% \; ; & E = 0.7 \text{ GeV (T2K)} \end{cases}$

Larger E is better.

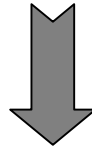But want L/E to correspond roughly to the peak of the oscillation.

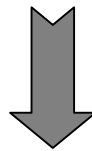Therefore, larger E should be matched by larger L.

Using larger L to determine whether the spectrum is normal or inverted could be a unique contribution of the U.S. program.

The APS Multi-Divisional Study

The compelling evidence that
neutrinos have mass and mix

⬇

Open questions about
the neutrino world

⬇

Need for a coherent strategy
for answering them

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This need has led to a year-long study of the future of neutrino physics, sponsored by the APS Divisions of –

Nuclear Physics

Particles and Fields

Astrophysics

Physics of Beams

The study website: www.interactions.org/neutrinostudy

A grassroots study like this, co-sponsored by several APS Divisions, is unprecedented.

It aims at consensus, which is not a trivial goal.

The study does not choose from among competing proposals to measure the same thing.

Rather, to quote the Charge —

"The Study will lay scientific groundwork for the choices that must be made during the next few years."

The Structure of the Study

Chairmen

Stuart Freedman, Boris Kayser

Organizing Committee

Janet Conrad, Guido Drexlin,
Belen Gavela, Takaaki Kajita,
Paul Langacker, Keith Olive,
Bob Palmer, Georg Raffelt,
Hamish Robertson, Stan Wojcicki
Lincoln Wolfenstein

Working Groups — The Central Element

Each working group is defined by an experimental approach.

The groups and their leaders —

Solar and Atmospheric Neutrino Experiments
John Bahcall, Josh Klein

Reactor Neutrino Experiments
Gabriela Barenboim, Ed Blucher

Superbeam Experiments and Development
Bill Marciano, Doug Michael

Neutrino Factory and Beta Beam Experiments and Development

Stephen Geer, Michael Zisman

Neutrinoless Double Beta Decay and Direct Searches for Neutrino Mass

Steve Elliott, Petr Vogel

What Cosmology/Astrophysics and Neutrino Physics can Teach Each Other

Steve Barwick, John Beacom

Theory Discussion Group

Rabi Mohapatra

Links to the working group reports are at
www.interactions.org/neutrinostudy

The integrated, cross-cutting heart of the study's final report is being written by the —

Writing Committee
Hamish Robertson
(Chair)
Janet Conrad, Andre de Gouvea,
Steve Elliott, Stuart Freedman,
Maury Goodman, Boris Kayser,
Josh Klein, Doug Michael

This committee submits its work to the study organizers and working group leaders.

The Status of the Study

It ain't over 'til it's over.

But we are close:

The study report will be posted for comment by all study participants in about 10 days.

A funding-agency briefing is planned for October 25.

The thrust of most of our major conclusions is fairly clear.

I will try to convey the flavor of most of them to you, emphasizing those related to a **proton driver**.

The Open Questions

Neutrinos and the New Paradigm

- What are the masses of the neutrinos?

- What is the pattern of mixing among the different types of neutrinos?

- Are neutrinos their own antiparticles?

- Do neutrinos violate the symmetry CP?

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Neutrinos and the Unexpected

- Are there "sterile" neutrinos?

- Do neutrinos have unexpected or exotic properties?

- What can neutrinos tell us about the models of new physics beyond the Standard Model?

Neutrinos and the Cosmos

- What is the role of neutrinos in shaping the universe?

- Is CP violation by neutrinos the key to understanding the matter – antimatter asymmetry of the universe?

- What can neutrinos reveal about the deep interior of the earth and sun, and about supernovae and other ultra high energy astrophysical phenomena?

Highlights of the Study Recommendations

PRELIMINARY

The recommendations are still under discussion.

But fairly broad consensus has emerged on a number of issues.

The Context

Our recommendations for a strong future U.S. program are predicated on fully capitalizing on our investments in the current program:

- Accelerator ν experiments within the U.S.

- American participation in experiments in Antarctica, Argentina, Canada, Germany, Italy, and Japan

The current/near-future program should include –

- Determination of the ^{7}Be solar neutrino flux to 5%.

- Clear-cut confirmation or refutation of LSND.

- R&D on techniques for detecting astrophysical neutrinos above 10^{15} eV.

- Measurements of neutrino cross sections needed for the interpretation of neutrino experiments.

An Important Observation

The future experiments we feel are particularly important rely on suitable **underground facilities**. Having these facilities will be crucial.

Proto – Recommendations for Future Experiments

High Priority: A comprehensive U.S. program to –

➢ Complete our understanding of neutrino mixing

➢ Determine whether the neutrino mass spectrum is normal or inverted

➢ Search for CP violation among the neutrinos

Components of this Program

- An expeditiously-deployed reactor experiment with sensitivity down to $\sin^2 2\theta_{13} = 0.01$

The size of CP violation and the ability to tell whether the mass spectrum is normal or inverted both depend on θ_{13}.

If $\sin^2 2\theta_{13} < 0.01$, a neutrino factory will be needed to study both of these issues.

A relatively modest-scale reactor experiment can cleanly determine whether $\sin^2 2\theta_{13} > 0.01$, and measure it if it is.

Sensitivity:

Experiment	$\sin^2 2\theta_{13}$
Present CHOOZ bound	0.2
Double CHOOZ	0.03 (In ~ 2013)
Future "US" experiment (Detectors at ~200 m and ~ 1.5 km)	0.01

- A timely accelerator experiment with the possibility of determining the character of the mass hierarchy

An accelerator ν experiment can probe several neutrino properties.

Only the U.S. can have baselines long enough to probe whether the spectrum is normal or inverted.

- A megawatt-class proton driver and neutrino superbeam with an appropriate large detector capable of observing CP violation

These facilities are needed if we are to be able to determine whether the spectrum is normal or inverted, and to observe CP violation, for any $\sin^2 2\theta_{13} > (0.01 – 0.02)$.

Why would C̶P̶ in ν oscillation be interesting?

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism
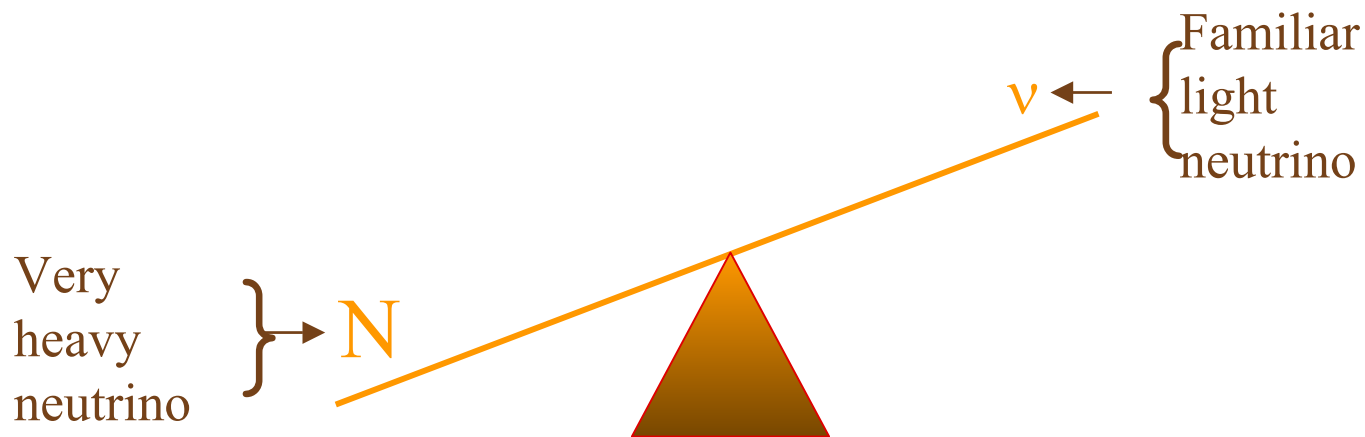
The heavy neutrinos N would have been made in the hot Big Bang.

If neutrino oscillation violates CP, then quite likely so does N decay.

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

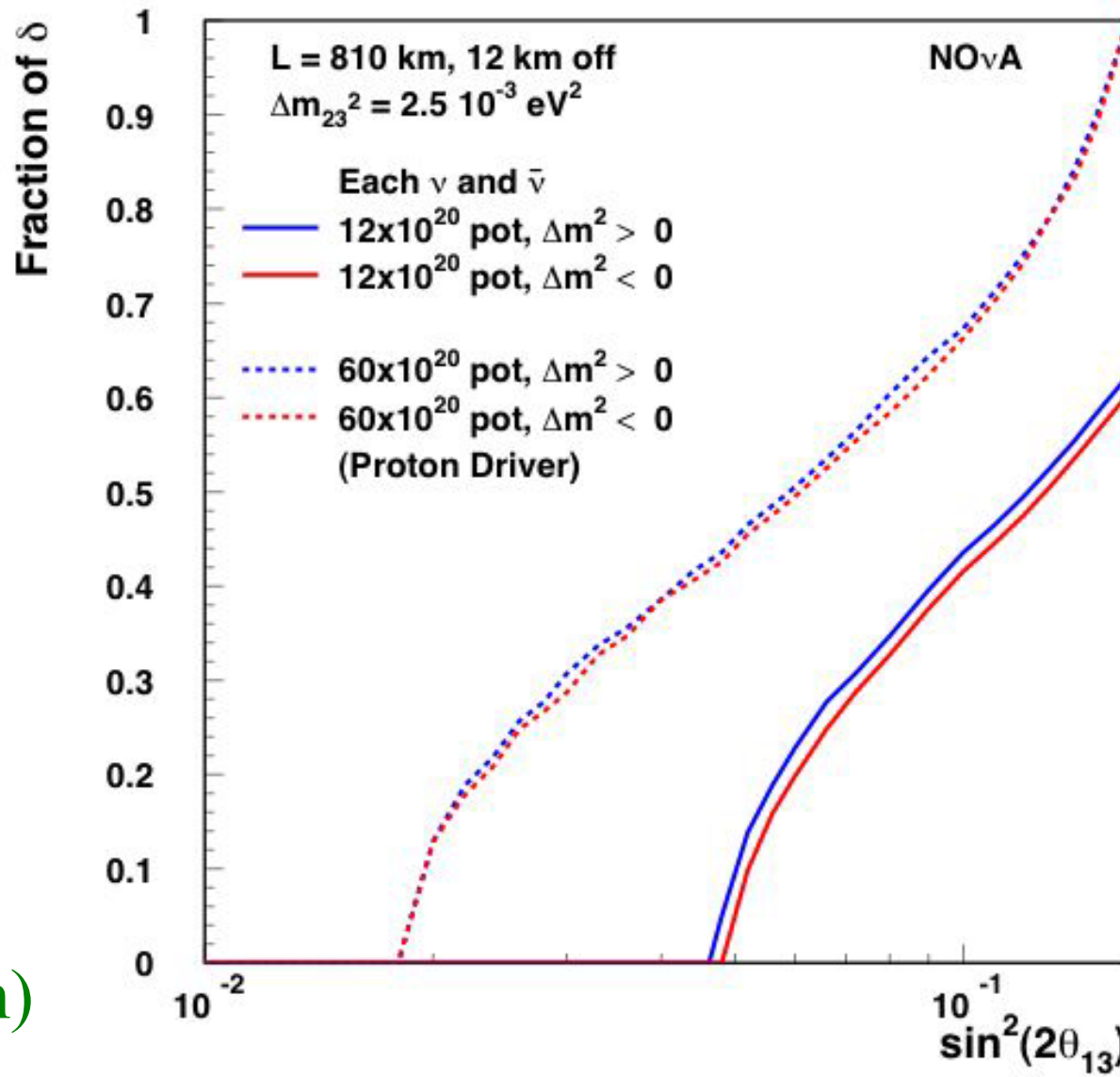$$N \rightarrow \ell^- + \dots \qquad \text{and} \qquad N \rightarrow \ell^+ + \dots$$

This would have led to unequal numbers of leptons and antileptons (Leptogenesis).

Perhaps this was the original source of the present preponderance of Matter over Antimatter in the universe.
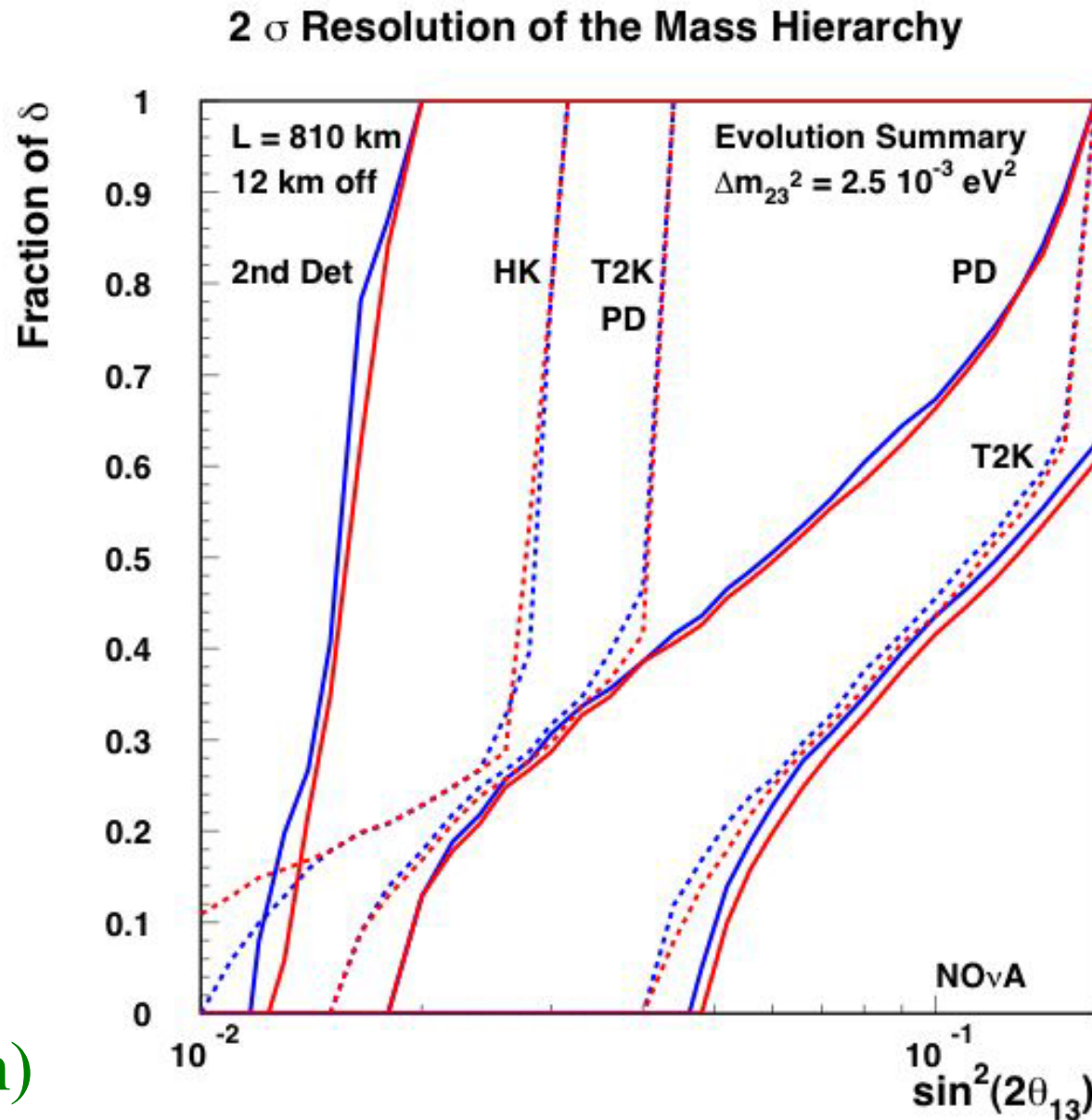
The Difference a Proton Driver Can Make

The spectral hierarchy without a proton driver

2 σ Resolution of the Mass Hierarchy

L = 810 km, 12 km off

$\Delta m_{23}^2 = 2.5 \; 10^{-3} \; eV^2$

NOvA

Each ν and $\bar{\nu}$

——— 12×10^{20} pot, $\Delta m^2 > 0$

——— 12×10^{20} pot, $\Delta m^2 < 0$

----- 60×10^{20} pot, $\Delta m^2 > 0$

----- 60×10^{20} pot, $\Delta m^2 < 0$

(Proton Driver)

Fraction of δ

$\sin^2(2\theta_{13})$

(Feldman)

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The spectral hierarchy with a proton driver

2 σ Resolution of the Mass Hierarchy

(Feldman)

CP violation without a proton driver

"… one cannot demonstrate CP violation for any delta without a proton driver."   (Feldman)
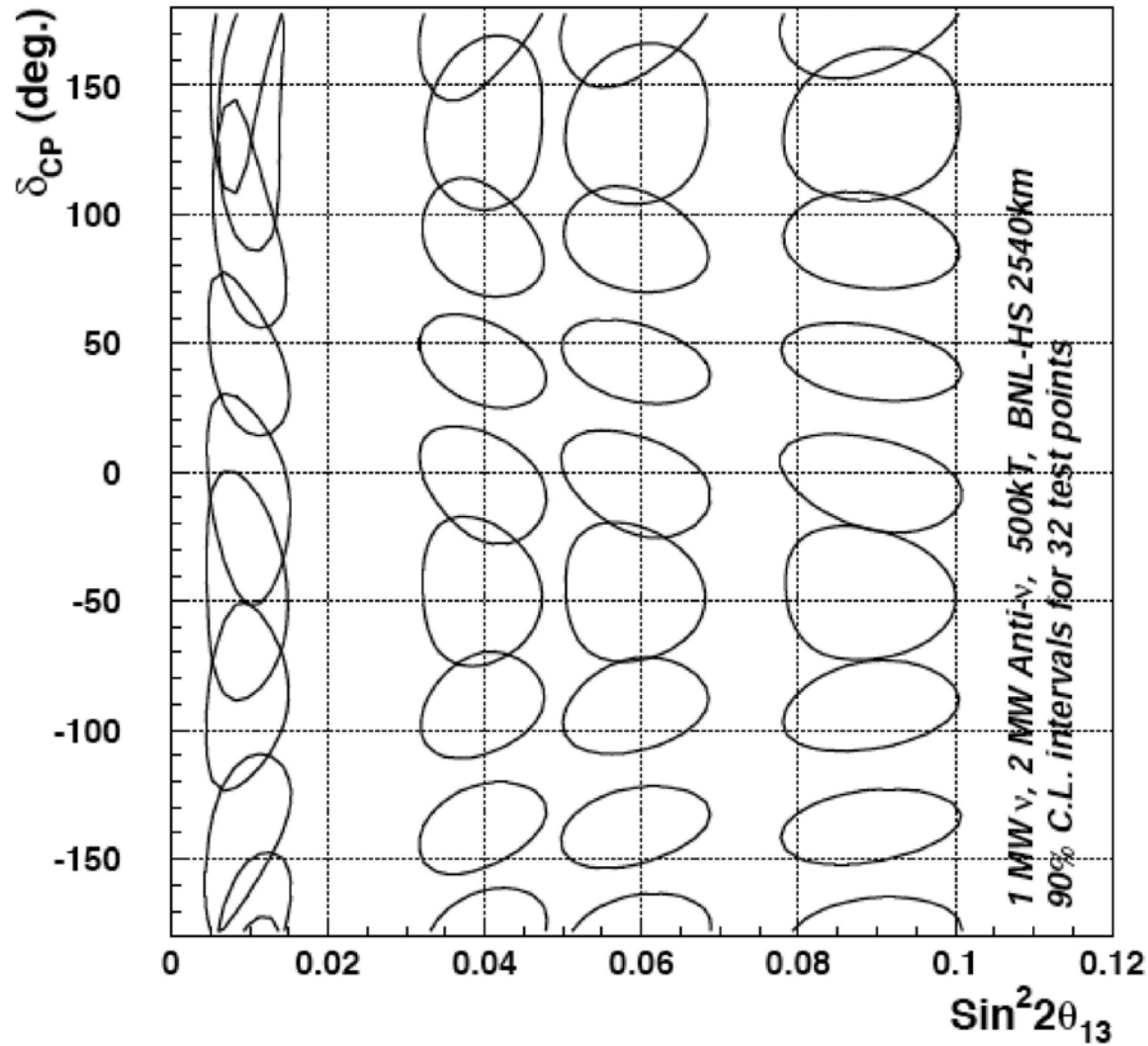
"Without a proton driver, one cannot make a 3 sigma CP discovery."   (Shaevitz)

CP violation with a proton driver

90% CL contours for 5 yr ν + 5 yr ν̄ running

(BNL)

High Priority: A phased program of searches for neutrinoless double beta decay ($0\nu\beta\beta$)

Observation of $0\nu\beta\beta$ would establish that –

- Lepton number L is not conserved

- Neutrinos are Majorana particles ($\bar{\nu} = \nu$)

- Nature *(but not the Standard Model)* contains Majorana neutrino masses

$$\text{Lifetime } (0\nu\beta\beta) \propto 1/[m_{\beta\beta}]^2$$

A phased 0νββ program addressing three possible $m_{\beta\beta}$ ranges:

Range (meV)	Spectrum Covered	Required Mass	Status
100 – 500	Quasi - Degenerate	200 kg	Close
20 – 50	Inverted	1 ton	"Proposed"
2 – 5	"Any"	100 tons	Future Tech.

In the first two stages, more than one experiment is desirable, worldwide, both to permit confirmation and to explore the underlying physics.

Looking Ahead

- A neutrino factory (or beta beam) is the ultimate tool in neutrino physics. It may be the *only* way to study CP violation and other issues. Substantial neutrino factory R&D is needed if this facility is to be possible in the long term.

Conclusion

We have a very rich opportunity to do exciting physics.

A **proton driver** would be a key component of the program.